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A Hybrid Simulation Approach for Microtunneling Construction Planning

Abstract

Purpose

Construction planning for microtunneling projects is a complex process due to the high level of uncertainties inherent in underground construction and the interdependent nature of decision variables. Simulation is a suitable decision-making tool to account for uncertainties and to model complex dependencies among decision variables. This paper aims to improve microtunneling construction planning by using simulation.

Design/methodology/approach

This study proposes a hybrid simulation approach that combines discrete event simulation (DES) with continuous simulation (CS) for microtunneling construction planning. In this approach, DES is used to model construction processes at the activity level, and CS is used to model the continuous flow of soil material in the system.

Findings

To demonstrate capability of the proposed approach in construction planning of microtunneling projects, different construction plan scenarios are compared in a microtunneling case study. The results of the case study show suitability of the hybrid DES-CS approach in simulating microtunneling construction processes, and the practicality of the approach for identifying the most efficient construction plan.

Originality/value

This study proposes a new modeling approach for microtunneling construction processes using hybrid simulation and provides decision supports at the construction planning stage of projects.

Key Words: Microtunneling, Construction Planning, Simulation, Hybrid Simulation, Decision Support, Uncertainty Modeling

Introduction

Planning of microtunneling construction, which is a linear process, relies on estimating the microtunnel boring machine (MTBM) production rate. To have a realistic productivity prediction, various considerations must be accounted for, including uncertainties surrounding underground construction; the efficiency of activities executed on the surface, such as the slurry separation system; failures or delays in the system; and interactions between the MTBM and soil removal system.

Unknown underground conditions are the main cause of uncertainty in estimating the MTBM production rate. Although most activities in microtunneling construction are executed underground, they can impact the overall efficiency of the microtunneling construction project. For instance, in the processes of excavation, slurry injected at the tunnel face is used for stabilizing the tunnel face and also for removing the excavated material from the tunnel face to the slurry plant. In the slurry plant, excavated material is separated from the slurry, and the slurry flow is then recycled and used later in the excavation process. Therefore, the slurry plant plays an important role for slurry excavation process. If any problem happens while recycling the slurry (e.g., material overflowing into the plant, clogging the sieves for separation process, or stopping in the process of removing the sedimented material out of the tank), the excavation process may halt, which impacts the total production rate. Therefore, decisions made on some variables, such as slurry container capacity, the number and size of employed trucks for removing excavated soil materials, or working shift hours, can affect the tunneling production rate. Such considerations complicate modeling the MTBM advance rate for productivity estimation. Simulation is a strong tool that can help to model these considerations and take into the account the uncertainties and the complex interactions among interdependent variables.

This paper is structured as follows: first, a literature review section is presented. Then, a description of microtunneling operations and the details of the simulation modeling are provided in the methodology section. The practicality of the proposed approach is demonstrated through its application to a case study, which is followed by evaluation of the model. Finally, the paper concludes with a discussion of the advantages of using the hybrid simulation modeling for estimating microtuneling productivity.

Literature review

Simulation is an effective tool for the analysis of construction operations due to its ability to consider the complexity and uncertainty inherent to construction activities (Halpin *et al*., 2003). Simulation modeling in construction has enabled practitioners to explore various project execution scenarios, supporting decision-making and reducing the uncertainty associated with project delivery (AbouRizk, 2010). Due to its ability to model the uncertainty and complex interactions between interdependent variables, many researchers have used simulation to support the planning of various aspects of tunneling projects (AbouRizk *et al*., 1999; Haas and Einstein, 2002; Einstein, 2004; Chung *et al*., 2006; Al-Bataineh, 2008; Liu *et al*., 2015). For example, Haas and Einstein (2002) and Einstein (2004) developed a computer-based tool, called decision aids for tunneling (DAT), that estimates tunnel construction time and cost based on the prediction of geological and geotechnical conditions by simulating construction operations. Chung *et al*. (2006) used Bayesian updating methods with simulation to model the productivity of utility construction. Al-Bataineh (2008) used a scenario-based simulation approach for planning tunneling projects. Liu *et al*. (2015) developed a geologic risks-aware and adaptive CYCLONE simulation for scheduling a tunneling project by predicting the probability of geological risks and rock types along the tunnel.

A hybrid DES-CS modeling approach has been successfully applied to model a variety of areas including, but not limited to, manufacturing and supply chain management (Lee *et al*., 2002; Venkateswaran *et al*., 2006), project planning (AbouRizk and Wales, 1997), train-pedestrian interactions (Ekyalimpa *et al*., 2016), pipeline construction (Shi and AbouRizk, 1998; Shahin *et al*., 2011), and to model the dynamic behavior of the construction environment (Alvanchi *et al*., 2011).

Although simulation has been studied extensively in tunneling, relatively few studies have used simulation for modeling microtunneling projects (Nido *et al*., 1999; Luo and Najafi, 2007; Marzouk *et al*., 2010; Dang, 2013; Dang *et al*., 2013; Conrads, 2017). Luo and Najafi (2007) analyzed and simulated the factors affecting productivity in an actual microtunneling field study. They studied the impact of variations in soil type on productivity of microtunneling excavation and aimed to correlate productivity with different soil types. Dang (2013) has also used simulation to model microtunneling operations, combining the work with system dynamic and agent-based methodologies to develop a framework that analyzes the relationship between soil types, interruptions, and productivity. It is important to note, however, that these previous studies focused on DES simulation and assumed that the excavation process by the MTBM and the process of removing the excavated material from the tunnel face are discrete.

Methodology

A hybrid DES-CS simulation approach was used to model microtunneling operations. For any operation simulation modeling, it is vital to know the processes under which a system is working, otherwise the simulation model would not appropriately represent the actual operation of the system. First, microtunneling and its and operation process are described. Then, factors influencing the productivity of microtunneling projects are discussed. Finally, details of the simulation model are explained.

Description of microtunneling operations

Microtunneling is a trenchless construction method for installing pipelines with the following main features (ASCE, 2001): (1) it is controlled remotely from a control room; (2) it is usually guided by using a laser projected onto a target in the MTBM; (3) a hydraulic jacking system continuously pushes the pipes and MTBM; and (4) the tunnel face is continuously supported to counterbalance the groundwater and earth pressure.

There are two major methods for microtunneling excavation – the slurry method and the auger method. In the slurry method, slurry is pumped to the face of the MTBM. Excavated materials mixed with slurry are transported to the driving shaft and discharged at the soil separation unit above the ground. In an auger type method, excavated materials are transported to the entry shaft by the auger in a casing pipe, and then hoisted to the surface by a crane. The slurry method is more versatile due to its ability to excavate under the water table and in unstable conditions (Luo, 2005). This paper focuses on construction planning of a microtunneling project using the slurry method, with particular emphasis on the excavation process and pipeline installation.

The microtunneling construction process begins by excavating and preparing the driving shaft, which involves setting up the jacking frame and hydraulic jacks, lowering the MTBM into the entry shaft, and installing the laser guidance system, as illustrated in Figure 1 (Luo, 2005). After lowering the MTBM, the excavation process, using the slurry method, begins by surveying the tunnel alignment and continues by lowering a pipe section into the shaft with a crane. Then, in the pipe installation task, the crew connects the slurry lines and hydraulic hoses in the new pipe segment to the previous section. Next, a hydraulic jack pushes the new pipe section with the MTBM while excavating the tunnel. At the same time, the excavated material is removed and transported to the slurry separation plant. This excavation process is repeated until the total length of the pipeline is installed. Once pipeline installation finished, the MTBM is removed through the receiving shaft, and other auxiliary equipment, such as jacking frames, are removed from the driving shaft (Luo, 2005). Since the spoil removal system has a limited capacity during construction operations, the spoil must be removed from the separation tank. Hence, spoil is dumped into a truck that travels and dumps the material, then returns to be loaded again.

In the microtunneling process, there are various delays that affect the project schedule that must be taken into consideration. Hegab and Smith (2007) defined delays in microtunneling as the "non-working time" resulting from any reason beyond the planned schedule. Important categories causing delays, as identified in literature, were considered in this study as follows: (1) delays due to MTBM clogging caused by excavation through cohesive soils, (2) delays due MTBM warming in extremely cold weather prior to initiating work, (3) delays due to slurry pump failures, and (4) delays due to other MTBM breakdowns, such as electrical problems.

Simulation modeling

The hybrid simulation approach is detailed in the following section. DES and CS variables are of the model are first identified, followed by an explanation of the governing differential equations emulating the continuous processes. Then, the approaches used for modeling decision variable interactions and uncertainties are elaborated. Finally, the developed model is presented followed by its validation.

a) DES and CS

DES models are run by advancing time in discrete segments based on events that occur in the model (AbouRizk *et al*., 2016). It is important to note that, in DES, the state of the system does not change between event occurrences (i.e., during the operation of an activity/task) (Pritsker and O'Reilly, 1999). DES begins with a given event that triggers subsequent events until the termination point is reached. It has been found suitable for modeling repetitive construction operations, such as tunneling and earthmoving (Lee *et al*., 2007).

In contrast to DES, CS allows for states of variables to change continuously between event occurrences (i.e., during the operation of an activity/task). The rates of change are represented by differential equations (AbouRizk *et al*., 2016), such as Equation 1 (Pritsker and O'Reilly, 1999).

$$S\,(t_2) = S\,(t_1) + \frac{ds}{dt} \times dt \qquad \text{Eq.1}$$

Where $\frac{ds}{dt}$ is the rate of change during a given duration (*dt*), and $S\,(t_1)$ and $S\,(t_2)$ are the values of continuous variables (i.e., stock in simulation language) at time (t_1) and (t_2), respectively.

In hybrid DES-CS, continuous variables are integrated within a DES model (AbouRizk *et al*., 2016), thereby creating the hybrid simulation model."

b) DES and CS variables

To model the operation of excavation process using simulation, some activities are discrete and are modeled using discrete task elements in DES (e.g., surveying, lowering the pipe section with the crane, and setting up the pipes with crews). Other activities are continuous and must be modeled as continuous tasks in CS. In this study, the continuous section of the model includes the

MTBM excavation process, spoil removal system, and removing the separated soils from the slurry at the separation plant (Figure 2).

Since the flow of soil material is continuous, the excavated tunnel length is modeled as a continuous variable in this study. Therefore, Eq. 2 can be derived from Eq. 1 to calculate the excavated tunnel length at each time.

$$Excavated\ tunnel\ length\ (t_2) = Excavated\ tunnel\ length\ (t_1) + \frac{dx}{dt} \times dt \qquad \text{Eq. 2}$$

In the above equation, $\frac{dx}{dt}$ is the penetration rate of the MTBM, and dt is the excavation duration in Equations 2–4. Therefore, by knowing penetration rate, the excavated tunnel length can be calculated. It should be noted that the penetration rate is not constant, as it depends on soil type.

Another continuous variable is the flow of the excavated soil in the slurry separation system. In this system, the inflow of material into the separation tank is the mixture of slurry with the excavated soils. The slurry is separated from the excavated soil in the separation tank, then the slurry is recycled and returned to the system to be used again in the excavation process. The outflow from the system is the separated soils remaining in the separation tank that must be removed and loaded into the trucks. Therefore, by knowing the inflow and outflow of material from the separation tank, the amount of remaining material in the separation tank (*VS*) can be calculated using Eq. 3.

$$VS(t_2) = VS\ (t_1) + \frac{(material\ inflow - material\ outflow)}{dt} \times dt \qquad \text{Eq. 3}$$

It should be noted that, in the above equation, the inflow is dependent on the MTBM penetration rate. The amount of material dumped into the truck at each time step (*VT*) is a function of the outflow rate ($\frac{dVT}{dt}$) and the volume remaining in the truck at the previous time step; therefore, Equation 4 is used to calculate the volume of material in the truck.

$$VT\,(t_2) = VT\,(t_1) + (\frac{dVT}{dt}) \times dt \quad \text{Eq. 4}$$

In a hybrid DES-CS simulation, there are three fundamental interactions between changes that occurs in discrete and continuous variables (Pritsker and O'Reilly,1999): (1) "a discrete change in value may be made to a continuous variable," (2) "an event involving a continuous state variable achieving a threshold value may cause an event to occur or to be scheduled," and (3) "the function description of continuous variables may be changed at discrete time instants."

In this hybrid simulation of a microtunneling project, the interactions between discrete and continuous variables exist when modeling the excavation process and slurry flow into the slurry separation plant.

For the excavated tunnel length variable, three thresholds can be considered, with the first two pertaining to the interactions between the DES and CS environments. The first threshold is used to permit the surveying activity to be completed. After excavating a certain amount of tunnel, the surveying activity must be performed again. During that time, the MTBM and crane may stop working. The second threshold is used to identify the completion of the excavation of one pipe section, the lowering of the next pipe, and the installation of this piece into position for the hydraulic jack. The third threshold is for adjusting the penetration rate frequently (e.g., every meter) according to the geotechnical conditions.

For *VS*, a maximum threshold must be determined to avoid overflowing the slurry separation plant. This threshold must be continuously monitored to stop material inflow, which in turn leads to halting the excavation process until sufficient material is removed from the slurry separation plant. Hence, another threshold is considered in the modeling to resume the excavation when space is available again. For *VT*, a threshold is considered to identify when the truck is full and allow for the truck travelling task to start in the DES model.

c) Rationale for implementing a hybrid DES-CS approach

As discussed previously, there are processes, particularly in tunneling operations, that are more accurately represented by CS. While activities, such as those associated with pipe installation, are well-represented by DES, continuous variability in the MTBM advance rate, balancing of the excavation rate with the slurry removal system, and accompanying system failures are not amenable to a DES-only approach. To address this challenge, this study proposes the use of a hybrid simulation approach to create a simulation model that is more representative of actual microtunneling operations. The proposed methodology facilitates the modeling of system interactions occurring during microtunneling, including phenomena such as MTBM interactions with the slurry separation plant where the performance of the slurry separation plant will affect MTBM advancement (and vice versa).

While the application of a hybrid DES-CS approach has been applied in construction engineering literature, it has yet to be applied to microtunneling construction—particularly with regards to the above-mentioned considerations (i.e., balancing of the excavation rate with the slurry removal system). The hybrid DES-CS modeling approach proposed here is capable of simulating (1) the effect of failures occurring during an activity, such as pump/MTBM breakdowns, and their effect on the entire operation of a system (Alzraiee *et al.*, 2012), (2) the effect of immediate corrective actions taken during an activity in response to failures (Alzraiee *et al.*, 2012), such as halting the excavation process to repair MTBM/pumps, and (3) the interactions between the continuous behaviors of a system, such as the excavation of a pipe section, and other discrete-event activities, such as the release of the hydraulic jack after excavation. Attempting to reflect these features in DES alone would results in false expectations of system productivity. To overcome this challenge, this study has applied existing simulation principles to enhance microtunneling planning by improving the state-of-the-art in microtunneling simulation.

Modeling decision variable interactions and uncertainties

Considering the interactions between decision variables and uncertainties inherent in microtunneling processes is not easy for planning. However, simulation is a strong tool that can help in this regard. The dependencies among decision variables and other uncertain construction parameters are described, with the causal loop diagram shown in Figure 3. The nodes in Figure 3 are variables, and edges show the relationships between them; positive (+) and negative (–) signs refer to positive and negative (inverse) influences, respectively (John, 2000).

The lack of space in the slurry separation plants causes delay in the project (Figure 3a). When the MTBM excavates faster, the material inflow into the slurry separation plant increases, leading to less available space in the slurry separation plant. Lack of space in the slurry separation plant can cause delays, as excavated materials are required to be pumped to the slurry separation plant. However, there is material outflow from the slurry separation plant as well (Figure 3c). If truck size or truck availability increases, this outflow increases. Truck availability depends on both truck cycle and number of trucks being used in the system. However, truck cycle is not only affected by the hauling distance, but also by weather conditions and precipitation. Precipitation may increase the truck cycle as traveling time increases. Factors contributing to potential delays of the system are detailed in Figure 3b. This includes cohesive soil type, which can affect MTBM cleaning time due to clogging. Weather conditions can also create delays by causing pump freezing or requiring extra warming time for the MTBM. Finally, other MTBM-related issues, such as electrical system or jacking system failures, can result in project delays. It is important to note that the weather temperature (Figure 3b) and precipitation (Figure 3c) are derived using a Markov chain Monte Carlo (MCMC)-based approach.

The MCMC approach is adopted in this hybrid simulation methodology to account for uncertainties in microtunneling due to weather conditions. A Markov chain process is a stochastic process that satisfies the Markov property in a way that the future state only depends on the current state (memoryless). In a (discrete-time) Markov chain, the state of the system moves at discrete time steps. It consists of a sequence of random variables (i.e., events), signified as $X_1, X_2, X_3,\ldots, X_{n+1}$, that satisfy the Markov property defined as Equation 5 (Asmussen, 2003), which states that the probability of each event $\Pr(X_{n+1})$ is dependent only on the previous event (Gagniuc, 2017).

$$\Pr\left(X_{n+1} = x \,\middle|\, X_n = x_n\right) \qquad \text{Eq. 5}$$

A Markov chain can be represented as a directed graph, with the vertices representing states and edges showing the probability transmission between states. The MCMC is a method for sampling from a probabilistic distribution of a continuous random variable by recording the states from the chain (Kroese *et al.*, 2014). Readers are referred to Asmussen (2003) and Gagniuc (2017) for more information on Markov chains.

a) Hybrid DES-CS simulation and model interactions

Interactions between the DES and CS models (excluding delays/breakdowns) for the base simulation of a microtunneling project are illustrated as a UML diagram in Figure 4. Here, the excavation procedure is set to begin during working hours if required resources, including the MTBM, are available. The excavated tunnel length, which is represented as a stock in the CS, is continuously monitored to determine the location of the MTBM. The penetration rate is then set based on the MTBM location and in consideration of geotechnical conditions. After excavation for a pipe length is complete, the DES is triggered to release the resources that have completed the excavation (i.e., MTBM and hydraulic jack). Then, the crane is set to lower the pipe, and the crew will begin installation of the new pipe section. The DES and CS models interact again during the survey operations portion of the work. The excavated tunnel stock is monitored, allowing excavation to be temporarily halted to allow surveying of the tunnel. Once the surveying is complete, operations are resumed in both the CS (e.g., excavation) and DES (e.g., installation) models. It is important to note that weather conditions are evaluated daily, as surveying may take longer in cold weather.

During the excavation, the inflow from the tunnel face to the plant must be established, which itself requires continuous monitoring for unloading decision purposes. When unloading is underway, the outflow from the plant to the truck must be initiated until the truck is fully loaded (i.e., another interaction between DES and CS), to begin the round trip between the site and dump area, which are all in DES. After returning to the site, trucks will be queued to start loading upon request.

Case study

To demonstrate the implementation of the proposed framework, a case study was developed. The project is a microtunneling excavation for pipe installation, with a total length of 300 meters and diameter of 1.5 meters. The precast pipe segments are each 3 meters long. A review of geotechnical baseline reports shows that the first 150 meters of the tunnel is sandy soil, while the rest is silty clay soil. Due to the limited capacity of the separation plant, a truck continuously travels between the site and dumping area to remove the separated soils. The survey operation is performed every 15 meters, and penetration rate is sampled every 1 meter based on Equation 6.

$$\text{Penetration Rate}\left(\frac{mm}{min}\right) = \begin{cases} \text{Triangular}(16,29,20), \textit{sandy soil} \\ \text{Triangular}(10,19,10), \textit{silty clay soil} \end{cases} \quad \text{Eq. 6}$$

Note that in Equation 6, Triangular (*a*, *b*, *c*) refers to the triangular probability distribution, where *a*, *b* and *c* are the minimum, maximum, and mode values, respectively.

In this project, the forecast for daily weather conditions is based on the MCMC model, with a transition interval of 24 hours (daily). The implemented Markov chain models are shown in Figure 5. The vertices of the graph in Figure 5 represent the states, and the edges represent the probability of transitioning from one state to another. For example, in Figure 5b, if the current state of the system is “without precipitation,” the next state (i.e., the next day) will remain the same with a probability of 80%, or “with precipitation” with a probability of 20%.

In this study, three decision variables, including (1) the capacity of the separation plant, (2) the size of the truck, and (3) working shift hours, were chosen to evaluate their influence on the productivity of the operation. The planning scenarios considered are presented in Table I, which also shows the project time and cost. Both a pure DES model and the proposed hybrid simulation model were applied to the scenarios described. In this case study, four types of delays were considered: (1) MTBM breakdowns, (2) slurry pump repairs, (3) MTBM cleaning, and (4) MTBM warming. Results of the total delays for each scenario are shown in Table I. As there are various uncertainties involved in this project (e.g., duration of each task, breakdowns, weather conditions and subsequent effects, etc.), the simulation had to run several times based on Monte Carlo simulation.

There are some assumptions in this case study. First, when the MTBM is not operating due to required repair or warming in cold weather, trucks can still remove soil from the separation plant. Second, during survey operations, the crane and MTBM do not operate.

To calculate project cost, the following costs were summed:

- Tunneling operation cost: tunneling operation cost, including equipment cost and crew, is \$14,000 or \$18,000 per day with 16-hour shifts or 24-hour shifts, respectively.
- Truck cost: operation cost of truck with 6 m^3 or 10 m^3 capacity are \$150 or \$170 per hour, respectively.
- Separation plant cost: Separation plant costs with the capacity of 19, 30, or 40 m^3 are \$200, \$300, or \$400 per day, respectively.

This case study was developed in the Simphony environment, *Simphony.Net*, version 4.6 (Hajjar and AbouRizk, 1996).

Analysis of the total project cost and time in the hybrid model (Table I) suggests that it is economically beneficial to use a 10m^3 truck in this project (i.e., Scenario 2 vs. Scenario 4). Furthermore, for the scenarios that use a larger size spoil removal system, the total project duration is less, which consequently reduces total project cost. Using a larger truck size and a larger-capacity slurry separation plant helps the system to balancing capacity, reducing the slurry separation plant's maximum threshold. It should be noted that increasing the capacity of the spoil removal system does not necessarily lead to a reduction in project time due to the limited power (i.e., excavation rate) of the MTBM, which itself limits the inflow rate of material into the plant. As a result, there is an optimal point for the size of the spoil removal system. This is illustrated in the hybrid model results in Scenario 10 (Table I), that, although uses the 40m^3 spoil removal system, results in the equivalent project duration and a greater project cost than Scenario 5, which uses the 30m^3 spoil removal system. Therefore, Scenario 5, which uses the large size truck and large capacity for spoil removal system, results in the minimum total project cost and time.

Variation in predicted project duration between the pure DES model and the hybrid simulation model ranged from 4% – 29%, with an 8% deviation observed in Scenario 5. Differences are primarily due to the CS portion of the hybrid simulation model, which allows users to control events within task performance. This is particularly important in microtunneling to account for interruptions during an activity due to equipment breakdown. In DES modeling, changes are only possible in event points (i.e., before or after discrete tasks), resulting in a lack of control over within-task operations.

The histogram and cumulative distribution for project duration from 100 runs of Scenario 5 (i.e., best scenario) is depicted in Figure 6. The project has a 90% probability of finishing in 27.3 days (Figure 6b), and the project duration ranges from 24.3 to 27.3 days with a confidence interval of 80% (Figure 6a).

To further elaborate on the influence of decision variables in planning, some scenarios are compared in Table II. For example, comparing Scenario 1 with Scenario 3 shows that using larger truck size, while keeping the shift and slurry separation plant the same, reduces project duration by 23%. Notably, it also demonstrates the sensitivity of the module to various decision variables.

Table III shows the source of delays and average duration for the best-case scenario (Scenario 5), with an average production rate of 12 meters per day. It also shows that the total delay for this scenario is 67.68 hours. This case study demonstrates the usefulness of using hybrid simulation framework for decision making in multi-variable system with complex interactions. Hence, using the simulation-based approach can lead to improve microtunneling construction planning by considerably reduce project time and cost.

Model verification and validation

The proposed framework was evaluated using four methods that have been comprehensively described by Sargent (2007), namely (1) a parameter variability-sensitivity analysis, (2) an extreme condition test, (3) an operational graph analysis test, and (4) a traces test. Results of the analyses are detailed in Table IV.

Conclusion

Planning microtunneling construction requires a decision-making system that accounts uncertain factors that affect productivity (e.g., MTBM penetration rate, weather condition, soil type, MTBM down time). This study enhanced planning of microtunneling construction operations for making decisions in multi-variable system by using a hybrid discrete event and continuous simulation approach capable of considering various uncertainties affecting the productivity of microtunneling project, as well as the interdependencies and interactions of the decision variables. This study also enhanced the accuracy of planning by modeling the continuous nature of the MTBM excavation process, balancing operations of the slurry plant, and the flow of excavated soil in the microtunneling project using CS. The developed model was implemented in a microtunneling case study, and the results are compared to the pure DES. The results showed that the developed model can assist decision makers in identifying the most efficient planning scenario in terms of project cost and time in microtunneling projects, with an in-depth analysis on how changing various variables impacts the project. The most efficient scenario (Scenario 5) reduced costs by 31% and time by 49% compared to the worst case scenario (Scenario 2).

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Table I – Characteristics of scenarios

Scenario number	Shift (hour)	Truck size (m^3)	Slurry plant capacity (m^3)	Hybrid model			DES model	
				Project duration (days)	Total cost ($1000)	Total delay (days)	Project duration (days)	Total cost ($1000)
Scenario 1	16	6	30	48	801.6	5.60	34	567.8
Scenario 2	16	6	19	49	813.4	6.12	40	664
Scenario 3	16	10	30	37	629.7	4.38	30	510.6
Scenario 4	16	10	19	38	642.9	4.64	33	558.3
Scenario 5	24	10	30	25	559.5	2.82	23	514.7
Scenario 6	24	10	19	27	601.5	3.08	25	557
Scenario 7	24	6	30	34	744.6	3.84	29	635.1
Scenario 8	24	6	19	35	763	4.06	33	719.4
Scenario 9	16	10	40	38	802.5	4.12	29	612.4
Scenario 10	24	10	40	25	562	2.96	24	539.5

Table II – Scenario comparison

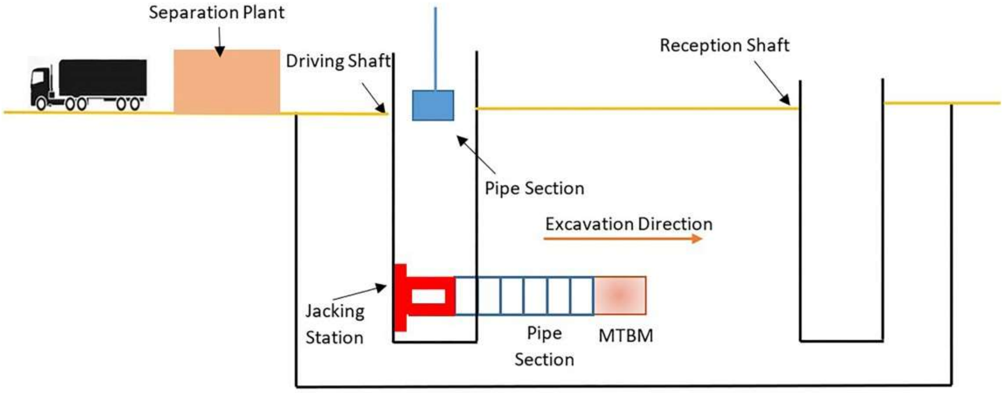
Scenario comparison	Decision variable comparison	Project duration improvement
Scenario 1 vs. 3	Truck 6m^3 vs. Truck 10 m^3	23%
Scenario 3 vs. 5	Shift 16 hr vs. Shift 24 hr	32%
Scenario 6 vs. 5	Separation Plant 19 m^3 vs. 30 m^3	7%

Table III – Source of delays and average duration in Scenario 5

Type of delay	Pump delay	MTBM warming	MTBM break down	MTBM cleaning	Total delay
Mean (hour)	16.32	3.6	30.7	16.56	67.68

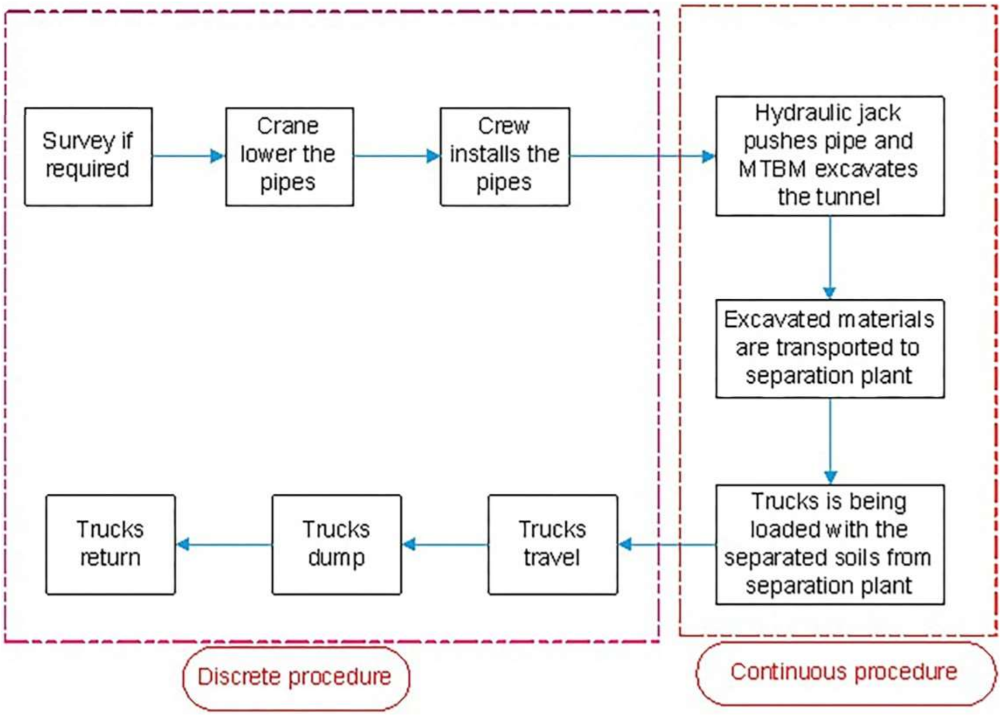
Table IV – Tests performed for verification and validation

Test	***Test process and results***
Parameter variability – sensitivity analysis	Various input values have been examined to capture their impact on model behavior and outputs. Here, truck size, spoil size, shift hours, probabilities in Markov chains, number of crews, probabilities of failures, and flow rates have been changed, and the resulting impact on the model's outputs have been assessed. The impact and trends observed were consistent with what is to be expected in a real system. For example, increasing project resources leads to a reduction in project duration—up to a certain point—where further increases can no longer decrease project duration. Some of the cases applied in the case study and the sensitivity analysis are detailed in Table II.
Extreme condition tests	The model was tested in extreme conditions, and resulting outputs were consistent with what is to be expected. For example, having zero capacity at the separation plant or setting pipelines to be installed equal to 0 resulted in a production rate of 0. Other extreme cases that were examined were 100% probability of failures with a very long duration for repairs. A production rate of 0 was observed after breakdowns, demonstrating that the system behavior matches expectations.
Operational graphics-graph analysis	Values of the stocks and flows into and out of the stocks are available in a graphical format in *Simphony.NET*. Consequently, the time points when the flows (in/out) have been stopped can be tracked. These can be tracked simultaneously alongside trace windows, allowing the reason for such pauses to be investigated. Using this approach, the tunnel excavation stock was assessed to ensure that it acts logically as expected (e.g., stopping the inflow must stop the excavated tunnel length stock).
Traces	Trace windows were used to evaluate the time and duration of the activities of the microtunneling operation, the volume of materials in the separation plant, as well as the number of installed pipes in tunneling and excavated tunnel length. This information was analyzed and compared with hand simulation of the specificmodel to ensure accuracy of the results.



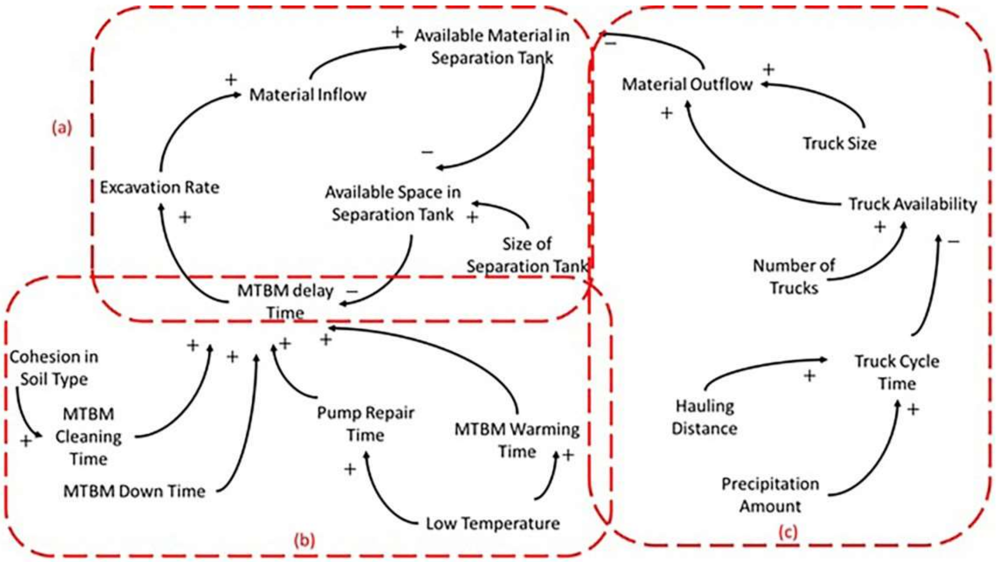
Schematic of a microtunneling operation

288x121mm (300 x 300 DPI)



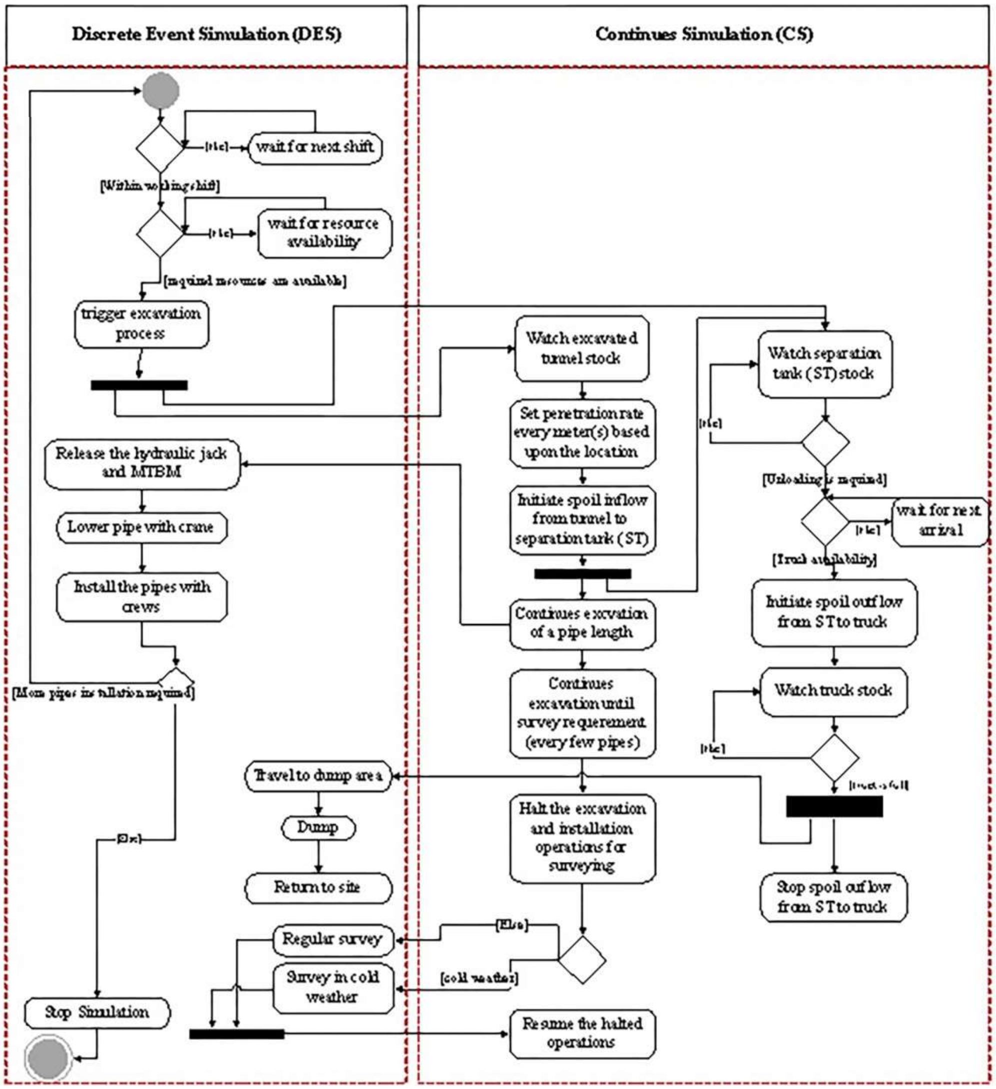
Model of microtunneling construction operations

160x114mm (300 x 300 DPI)



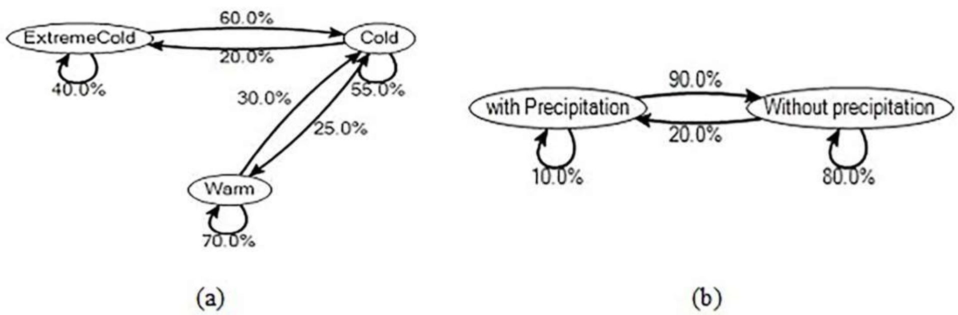
Causal loop diagram

168x93mm (300 x 300 DPI)



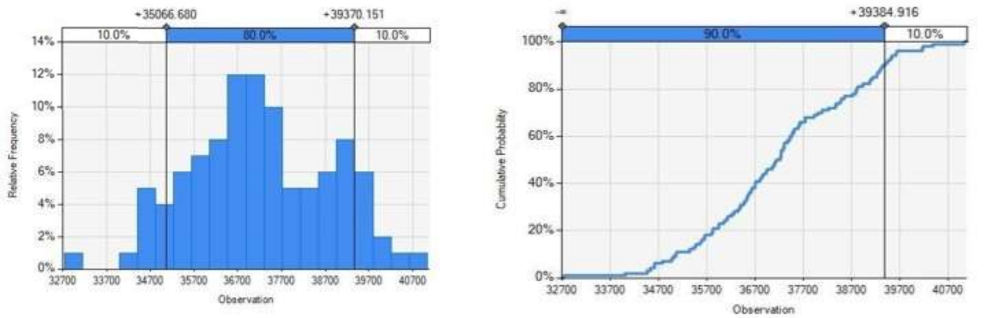
UML activity diagram of microtunneling simulation

158x171mm (300 x 300 DPI)



Markov chain for (a) weather temperature and (b) precipitation

208x70mm (300 x 300 DPI)



a) Histogram of project duration (Minute) b) Cumulative distribution of project duration (Minute)

(a) Histogram and (b) cumulative distribution of project duration for scenario 5 (in minutes)
192x70mm (96 x 96 DPI)